CERTIFICATE OF TRANSMISSION BY FACSIMILE (37 CFR 1.8) Applicant(s): Morton et al.			Docket No 2001-0138-03
Application No. 10/629,364	Filing Date 7/29/03	Examiner B. Talbot	Group Art Unit 6284

Invention: HIGH REP-RATE LASER WITH IMPROVED ELECTRODES (Trans Appeal Brief -1 pg; Pet EOT -1 pg; Appeal Brief w/Appendices 12 pgs; Attachment 10 -pgs & Dep Acct Sheets (2)

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P18/REV02

TRANSMITTAL OF APPEAL BRIEF (Large Entity)	Docket No. 2001-0138-03

In Re Application Of: Morton et al

Application No.	Filing Date	Examiner	Customer No.	Group Art Unit	Confirmation No.
10/629,364	7/29/03	B. Talbot	21773	1762	6284

Invention: HIGH REP-RATE LASER WITH IMPROVED ELECTRODES

COMMISSIONER FOR PATENTS:

Transmitted herewith is the Appeal Brief in this application, with respect to the Notice of Appeal filed on January 26, 2006

The fee for filing this Appeal Brief is: $500.00

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☒ The Director has already been authorized to charge fees in this application to a Deposit Account.

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Signature

Dated: April 26, 2006

William C. Cray, Reg. No. 27,627
Cymer, Inc.
Legal Dept. MS/4-2C
17075 Thornmint Court
San Diego, California 92127
Telephone: 858.385.7185
Facsimile: 858.385.6025

04/27/2006 TL0111 00000054 034060 10629364

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Signature of Person Mailing Correspondence

Stephanie Sharrett

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P30LARGE/REV07

PETITION FOR EXTENSION OF TIME UNDER 37 CFR 1.136(a) (Large Entity)	Docket No. 2001-0138-03

In Re Application Of: Morton et al.

Application No.	Filing Date	Examiner	Customer No.	Group Art Unit	Confirmation No.
10/629,364	7/29/03	B. Talbot	21773	1762	6284

Invention: HIGH REP-RATE LASER WITH IMPROVED ELECTRODES

COMMISSIONER FOR PATENTS:

This is a request under the provisions of 37 CFR 1.136(a) to extend the period for filing a response to the Office Action of Ntc of App 1/26/06 above-identified application.
Date

The requested extension is as follows (check time period desired):

☒ One month ☐ Two months ☐ Three months ☐ Four months ☐ Five months

from: March 26, 2006 until: April 26, 2006
Date *Date*

The fee for the extension of time is $120 and is to be paid as follows:

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Signature

Dated: April 26, 2006

William C. Cray, Reg. No. 27,627
Cymer, Inc.
Legal Dept. MS/4-2C
17075 Thornmint Court
San Diego, California 92127
Telephone: 858.385.7185
Facsimile: 858.385.6025

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Signature of Person Mailing Correspondence

Stephanie Sharrett
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USSN 10/629,364
Atty. Docket No. 2001-0138-03

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:

Morton, et al.

Serial No.: 10/629,364

Filing Date: July 29, 2003

Title: HIGH REP-RATE LASER WITH IMPROVED ELECTRODES

Examiner: Talbot, Brian K.

Group Art Unit: 1762

Conf. No.: 6284

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APPLICANT'S APPEAL BRIEF

In response to a Final Office Action mailed September 26, 2005, Applicants submitted a Notice of Appeal in the above captioned application on January 26, 2006. Applicants hereby present Applicants' Appeal Brief.

(1) Real Party In Interest

The real party in interest in the above captioned application is Cymer, Inc. a corporation of the State of Nevada and the assignee of the above captioned application from the applicants, the named inventors.

(2) Related Appeals and Interferences

There are no related appeals or interferences.

(3) Status of the Claims

Claims 25-28 and 31 are pending in the above captioned application. Claims 25-28 and 31 stand rejected.[1] Claims 26 and 28 have been indicated to be allowable if amended to "overcome the rejections under 35 U.S.C. § 112 ... and to include the limitations of the base claim and any intervening claims."

(4) Status of Amendments

There are no outstanding amendments to the above captioned application.

(5) Statement of the Invention

The specification of the above captioned applications describes aspects of an embodiment of the claimed invention as follows:

> In preferred embodiments the two-material electrode is an anode of a fluorine containing gas discharge laser. A portion of the anode located at the discharge surface of the anode, is comprised of an anode material containing lead along with other metals chosen to produce during operation a porous insulating layer covering the discharge surface of the anode. The layer is produced by fluorine ion sputtering of the anode surface which creates the insulating layer comprised in part of lead fluoride as well as fluorides of other metals. ... When the anode is installed in the laser and is subjected to pulse discharges in a fluorine containing laser gas environment an insulating layer, comprising porous lead fluoride, forms on the surface of the first part protecting it from significant erosion. Applicants' computer electric field models have shown that the insulating layer does not significantly affect the electric field between the cathode and the anode. ... About 50,000 small holes develop in the insulating layer on the first part which permit electrons to flow freely to and from the metal surface of the anode. However, fluorine ion sputtering on the metal surface of the anode is substantially limited after the insulating layer has developed. Applicants believe that the

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[1] The September 26, 2005 Office Action states that claims 25-28 and 31 stand rejected. However, claims 26 and 28 were only rejected for obviousness double patenting, which applicants intend to deal with by terminal disclaimer in any continuing prosecution of the above captioned application after the decision in this appeal. Nevertheless rejections of claims 26 and 28 appear to have been made by the Examiner under 35 U.S.C. §112, even though the Examiner has not included them in the §112 rejection in the body of the Office Action and has indicated they would be allowable if rewritten to overcome the §112 rejections and include the recitations of the claims from which they depend. they include recitations the Examiner finds indefinite and are included in applicant's arguments regarding the §112 rejection.

reduction in fluorine ion sputtering results from a reduced number of fluorine ions reaching the metal surface and a reduction in energy of the ions that do reach the metal surface. (p. 5, line 5- p. 6, line 3)

(6) Issues

1. Whether claims 25, 27 and 31 were properly rejected under 35 U.S.C. §102 with an inherency assertion.[2]

2. Whether claim 25-28 and 31 were properly rejected under 35 US.C. §112, second paragraph.[3]

(7) Claim Grouping

Claims 25, 27 and 31 stand and fall together with respect to, respectively, the §103 (a) rejection (102 (b) with inherency rejection) and the §112 rejection. Claims 26 and 28 stand together with claims 25, 27 and 31 only with respect to the rejection under 35 U.S.C. §112.

(8) Argument

(a) Facts

With respect to the rejection of Claims 25-28 and 31[4] under 35 U.S. C. §112, second paragraph, as being indefinite, the Examiner has taken the position that "the terms 'operating' and 'creating' are vague and indefinite as the claim fails to recite how these processes are performed.

With respect to the rejection of claims 25, 27 and 31 under 35 U.S.C. §103 (a), the Examiner has taken the position that these claims are unpatentable over United States Patent No. 3828277, issued to Otto et al. on August 6 1974, entitled INTEGRAL CAPACITOR LATERAL DISCHARGE LASER ("Otto") in view of United States Patent No. 5771259, issued to Dvorkin on June 23, 1998, entitled LASER ELECTRONIC COATING ("Dvorkin"), or JP01-154,577, published on June 16, 1989, entitled DISCHARGE EXCITATION TYPE SHORT PULSE LASER ("Yamazaki"). The Examiner has further taken the position[5] that:

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[2] See fn. 5.
[3] The specific rejection only includes claims 25, 27 and 31, but applicants respond as if it listed claims 25-28 and 31. See, fn. 1
[4] See fn.'s 1 and 3.
[5] In the "Response to Amendment" section of the September 26, 2005 Office Action.

Applicant argued the prior art fails to teach the coating on the electrodes to be porous.

The processes are both detailing coating an elongated electrode in lasers which is required to be porous in order to perform the function of allowing flow between the metal surface and anode while limiting the ion interaction of the laser gas components. Hence the porosity of the claimed coating layer would be inherently similar.[6]

b) Applicable Law

1) Anticipation By Inherency

An invention is patentable under 35 U.S.C. §102 unless anticipated by the prior art. Anticipation occurs if "'a prior art reference ... disclose[s] every limitation of the claimed invention, either explicitly or inherently.'" *Mehl/Biophile International Corp. v. Milgraum*, 192 F.3d 1362, 1365, 52 U.S.P.Q.2d 1303, 1305 (Fed. Cir. 1999); *General Electric Co. v. Nintendo*, 179 F.3d 1350, 1356, 50 U.S.P.Q.2d 1910, 1912 (Fed. Cir. 1999) ("anticipation requires that a single prior art reference disclose every limitation in a patent claim."); *Union Oil Co. of California v. Atlantic Richfield Co.*, 208 F.3d 989, 994-95, 54 U.S.P.Q.2d 1227, 1230-31 (Fed Cir. 2000) ("a party seeking to invalidate a patent under §102 [must] show that the allegedly invalidating prior art contains 'each and every element of [the] claimed invention.'"); *Richardson v. Suzuki Motor Co.*, 868 F.2d 1226, 1236, 9 U.S.P.Q.2d 1913, 1920 (Fed. Cir. 1989) (quoted in the USPTO Manual of Patent Examining Procedure, "MPEP" §2131); *Verdegaal Bros. v. Union Oil Co. of California*, 814 F.2d 628, 631, 2 U.S.P.Q.2d 1051, 1053 (Fed. Cir. 1987) (quoted in the MPEP).

Inherency "'may not be established by probabilities or possibilities. ... [T]he disclosure [must be] sufficient to show that the natural result flowing from the operation

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[6] Applicants assert that the rejection under 35 U.S.C. §103 (a), thusly stated, is a rejection under 35 U.S.C. §102 asserting electrode porosity to be inherent in one of the cited references. The Examiner had also made the 35 U.S.C. §103 (a) rejection as currently stated in the September 26, 2005 Office Action in an earlier Office Action of Aril 14, 2005, stating that the only difference with the claims was an optimization of length of the claimed electrodes. Applicants responded in a Response dated July 14, 2005 that in addition the claims recited that the electrode coating was porous. Applicants' position is that regardless of the validity of the "optimization" argument of the Examiner, which applicants do not concede is correct and reserve the right to challenge in any continuing prosecution after this appeal is decided, the claims are distinguished over the cited art, e.g., due to the porosity recitation. Therefore applicants herein respond to the rejection of claims 25, 27 and 31 stated to be under 35 U.S.C. §103 (a) as, in reality, a rejection under 35 U.S.C. §102 with an assertion of inherency.

as taught would result in the performance of the questioned function ... .'" *Mehl/Biophile*, 192 F.3d at 1365, 52 U.S.P.Q.2d at 1305; and *In re Robertson*, 169 F.3d 743, 745, 49 USPQ2d 1949 (Fed. Cir. 1999) ("[E]xtrinsic evidence 'must make clear that the missing descriptive matter is necessarily present in the thing described in the reference, and that it would be so recognized by persons of ordinary skill. ... The mere fact that a certain thing may result from a given set of circumstances is not sufficient.'")

2) Definiteness

To withstand a rejection based on indefiniteness under 35 U.S.C. §112 a claim must define the subject matter "with a reasonable degree of particularity and distinctness" and "apprise[] one of ordinary skill in the art of its scope and, therefore, serve[] the notice function required by 35 U.S.C. 112."[7]

d) Analysis

1) Issue 1

Applicants submit that there is nothing in any of the references Otto, Dvorkin or Yamazaki which in any way suggests that the dielectric used in those patents are porous or inherently must be porous. In fact, Yamazaki specifically discloses the dielectric is a coating on an "auxiliary" electrode, known in the laser art as a "preionizer." Preionizers create ions in a laser gas discharge region between the main discharge electrodes prior to the main discharge. This is known in the art to be due to a corona discharge at the surface of the dielectric covering a preionizer "auxiliary" electrode, which is generally a solid non-porous dielectric material such as a ceramic material. Yamazaki specifically refers to the generation of a corona discharge.

Applicants submit that both Otto and Dvorik suggest that this type of discharge, or something like it, other than one involving current flow from the coated electrode to another electrode, as what is disclosed. Dvorik notes that the dielectric coating covering one electrode there is for the purpose of reducing the power put into the CO_2 laser gas discharge, since lower power is sufficient of excite the CO_2 molecules to most of the relevant transition levels while reducing significantly the destabilization of the laser gas lasing medium due to dissociating the CO_2. (Col. 1, lines 32-52; Col. 3, lines 38-50; Col. 4, lines 45-47)

[7] M.P.E.P. 2173.02.

Otto notes that the purpose of the dielectric layer covering one of its electrodes is to distribute the electric field building up in the dielectric until the voltage across the capacitor formed by the two electrodes, the solid dielectric and the dielectric formed in the gaseous material, results in ions forming in the gas and a dielectric breakdown occurs in the gas (not the solid ceramic dielectric.

The dielectric in the form of a gas can be restored from the results of any discharge through the gas dielectric – dielectric breakdown. For solid dielectrics exposure to enough voltage across the plates of the capacitor (the opposing main electrodes) to cause breakdown in the solid dielectric material caused irreversible damage.

Thus in the operation of either Otto or Dvorik, the discharge cannot be one which results in electron flow to or from the one electrode covered by the dielectric material through the dielectric material itself. Rather electrons flow to or from the other electrode in a direction tending to reduce and/or eliminate the electric field built up in the combination of solid and gaseous dielectrics between the main electrodes.

Applicant respectfully requests the Board to take notice of the definition of a dielectric material and its properties attached to this Appeal Brief and which was taken from the identified URL. The same is true of the attached paper by Veldhuizen, et al, found at http: // www. phys.tue.nl/FLTPD/invited/veldhuizen . pdf discussing corona and like discharges from electrodes having a solid or gaseous dielectric material, or both, between them.

As noted in the description of a dielectric, it does not conduct but does allow energy to be stored in the form of an electric field, and depending on the strength of the dielectric current will not flow from the one electrode (capacitor plate) to the other unless the dielectric breaks down. Breakdown, as noted, especially with solid dielectrics usually results in irreparable damage to the dielectric.

Gas discharge lasers, however, operate with discharges occurring through the gaseous dielectric material over and over, and, e.g., with excimer lasers, the ions created in the gas return to ground state before the next discharge allowing the next discharge.[8]

Therefore, as is well known in the art, the disclosure of a gas laser with a dielectric coating on one of its main electrodes does not mean that the dielectric necessarily has to be porous for the disclosed laser to work or that the natural result of such an arrangement is the requirement that the dielectric material be porous. In fact, if these lasers worked as the Examiner's suggests, the breakdown of the ceramic dielectric would be permanent and/or the desired effects of using such a coated main electrode noted in either Otto or Dvorkin would thereafter by eliminated due to the irreversible harm to the ceramic dielectric material.

2) Issue 2

Applicants' submit that the recitations of the claims utilizing gerunds such as "operating" and "creating" are entirely permissible in method or process claims as specifically provided for in 35 U.S.C. §112, sixth paragraph as a "step for performing a specified function without the recital of structure, material, or acts in support thereof, ..." In addition, the claims as drafted define the subject matter being claimed "with a reasonable degree of particularity and distinctness" and "apprise[] one of ordinary skill in the art of [their] scope and, therefore, serve[] the notice function required by 35 U.S.C. 112."[9] The Specification of the above captioned application, further, fully describes how the operation of the particular type of laser, a fluorine gas discharge laser, serves to create the porous dielectric coating on the electrode.

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[8] To increase repetition rate, e.g., in excimer gas discharge lasers, the gas may be circulated so that fresh gas is moved to the discharge region for each new discharge and the gas may be cooled in the circulating process so that the ions have essentially all returned to ground state by the time a discharge again occurs in the circulated gas.
[9] M.P.E.P. 2173.02.

Conclusion

For the above stated reasons applicants assert that the Examiner's rejections of claims 26-28 and 31 are improper and respectfully request that the Board instruct the Examiner to withdraw the rejection of claims 26-28 and 31 and allow claims 26-28 and 31. The Commissioner is hereby authorized to charge the deposit account of applicants' assignee, Cymer, Inc., Deposit Account No. 03-4060 in the amount of $500.00 for the filing of the Applicants' Appeal Brief and $120.00 for a one-month extension of time to file this Appeal Brief. Applicants do not believe that any additional fees or charges are due for the prosecution of this appeal, however, in the event that there are, the Commissioner is authorized to charge any such additional fees or charges to the noted Deposit Account.

Respectfully submitted,

William C. Cray, Reg. No. 27,627

April 26, 2006
Cymer, Inc.
Customer No. 21773
Telephone: (858) 385-7185
Facsimile: (858) 385-6025

Appeal Brief Appendix 1
Claims
10/629,364

1.-24. (cancelled)

25. (previously presented) A process for producing an elongated electrode for use in a laser comprising the steps of:

    a) using an elongated electrode structure comprised of one or more electrical conducting materials and having a long dimension of at least 50 centimeters and a width of at least 3 centimeters.

    b) creating a porous insulating layer on a portion of the elongated electrode, the portion defining a discharge region having a width of at least 3 millimeters.

26. (original) A process as in Claim 25 wherein the one or more electrically conducting materials comprise a lead rich brass having a lead content of greater than 1 percent, and the step of creating the porous electrical insulating layer comprises operating the electrode in a fluorine containing laser gas to permit a porous insulating layer to build up on the lead rich brass.

27. (original) A process as in Claim 25 wherein the step of creating the porous insulating layer comprises spreading insulating particles on the discharge region of the elongated electrode structure.

28. (original) A process as in Claim 25 wherein said step of creating the porous insulating layer comprises the steps of:

    a) mixing insulating particles in a molten metal to produce a discharge section of the elongated electrode the section comprising a filler metal and the insulating particles,

    b) operating the elongated electrode in a fluorine containing laser gas environment to permit a portion of the filler metal to sputter

away leaving a porous insulating layer covering the discharge region.

29.-30. (cancelled)

31. A process as in Claim 25 wherein the step of creation of porous insulating layer includes the substeps of:

a. creating a plurality of nucleation sites on the discharge surface;

b. operating the electrode in a laser containing fluorine gas so as to permit the porous insulating layer to grow on the discharge surface.

32.-52. (cancelled)

Appeal Brief Appendix

10/629,364

Related Proceedings

None

Appeal Brief Appendix

10/629,364

Evidence

http://whatis.techtarget.com/definition/0,,sid9_gci211945,00.html

A dielectric material is a substance that is a poor conductor of electricity, but an efficient supporter of electrostatic fields If the flow of current between opposite electric charge poles is kept to a minimum while the electrostatic lines of flux are not impeded or interrupted, an electrostatic field can store energy. This property is useful in capacitors, especially at radio frequencies. Dielectric materials are also used in the construction of radio-frequency transmission lines.

In practice, most dielectric materials are solid. Examples include porcelain (ceramic), mica, glass, plastics, and the oxides of various metals. Some liquids and gases can serve as good dielectric materials. Dry air is an excellent dielectric, and is used in variable capacitors and some types of transmission lines. Distilled water is a fair dielectric. A vacuum is an exceptionally efficient dielectric.

An important property of a dielectric is its ability to support an electrostatic field while dissipating minimal energy in the form of heat. The lower the *dielectric loss* (the proportion of energy lost as heat), the more effective is a dielectric material Another consideration is the *dielectric constant*, the extent to which a substance concentrates the electrostatic lines of flux. Substances with a low dielectric constant include a perfect vacuum, dry air, and most pure, dry gases such as helium and nitrogen. Materials with moderate dielectric constants include ceramics, distilled water, paper, mica, polyethylene, and glass. Metal oxides, in general, have high dielectric constants.

The prime asset of high-dielectric-constant substances, such as aluminum oxide, is the fact that they make possible the manufacture of high-value capacitors with small physical volume. But these materials are generally not able to withstand electrostatic fields as intense as low-dielectric-constant substances such as air. If the voltage across a dielectric material becomes too great -- that is, if the electrostatic field becomes too intense -- the material will suddenly begin to conduct current. This phenomenon is called *dielectric breakdown*. In components that use gases or liquids as the dielectric medium, this condition reverses itself if the voltage decreases below the critical point. But in components containing solid dielectrics, dielectric breakdown usually results in permanent damage.

Corona discharges: fundamentals and diagnostics

E.M. van Veldhuizen, W.R. Rutgers
Faculty of Applied Physics, Technische Universiteit Eindhoven
PO Box 513, 5600 MB Eindhoven, The Netherlands

Introduction

Corona discharges are discussed in this paper as one example of pulsed atmospheric discharges. Other configurations used are the dielectric barrier and the packed bed reactor. Here only the volume discharge will be discussed and not the surface discharge that also plays a role in these last two cases.

The paper is divided in two parts. Fundamental processes that are important in corona discharges are treated in the first section. The characteristic properties of the corona will show up clearly here, its fast development in time and space being a dominating feature. It will also be indicated where knowledge of the processes involved is still marginal or even missing.

The second part gives an overview of experimental diagnostics that are in use to obtain data of the propagating discharge. Commonly used methods are treated as well as state-of-the-art developments.

General aspects of discharges at atmospheric pressure

Discharges at a pressure of 1 bar have several appearances. Lightning is one of them and although it is known with most people it is difficult to describe the lightning discharge in detail. In terms of discharges it is an arc with rather short duration and high power density. Arcs are also used in a more controlled way for instance for welding, high voltage circuit breakers or certain types of lamps. Arcs with duration in the microsecond range are usually called sparks and they are often observed at switching contacts. In case of high voltage applications breakdown can cause severe damage. Even shorter discharges can be created which in fact stop before they are completed in to arcs. These are sometimes called transient discharges and have typical time duration in the range of nanoseconds. There are two ways to create these discharges. A dielectric layer can cover one or two of the electrodes in the discharge gap. At a sufficiently high voltage between the electrodes the discharge starts in the gas volume. It spreads out until it reaches the electrodes but at the dielectric it builds up a space charge that cancel the applied electric field. At that moment the discharge stops. This discharge is usually called dielectric barrier discharge. The second method is to use an asymmetric electrode pair. Then the discharge develops in the high field region near the sharp electrode and it spreads out towards the cathode. In this case there are two possibilities to avoid the transition in to an arc. First the voltage can be made low enough to stop the spreading of the discharge somewhere before the cathode is reached. Second one can stop or lower the voltage when the cathode is reached. In the second way more energy can be put on to the discharge but it is more difficult to make the power supply. This type of discharge is called corona. It is a positive corona when the electrode with the strongest curvature is connected to the positive output of the power supply and a negative corona when this electrode is connected to the negative terminal of the power supply. In corona discharges at relatively low voltages the discharge stops itself due to the build up of space charge near the sharp electrode. This space charge then disappears due to diffusion and recombination and a new discharge pulse appears. This is the self-repetitive corona and it occurs in the positive and in the negative case.

Atmospheric discharges are under investigation since two decades for many environmental purposes [1]. The corona discharge and the barrier discharge are both good candidates in these applications. It is still an open question which type of discharge has the highest efficiency in plasmachemical applications. It appears that the barrier discharge can achieve higher electrical power densities but the corona discharge may be easier scalable to large gas flows. The barrier discharge is more complicated since it is a combination of a gas discharge and a surface discharge along the dielectric. This article is restricted from now on to the corona discharge. Only the positive corona will be discussed in detail since it was shown in many cases to be more effective than the negative case.

Development steps

The growing of the (positive) corona discharge will now be treated in more detail. Several steps are part of this process:

1. An asymmetric electrode configuration must be made
2. A high voltage must be applied
3. Some free electric charge must be present
4. An avalanche must build up and leave behind a space charge area
5. Photons from the avalanche create new charge carriers outside the space charge area
6. New avalanches develop closer to the cathode

Ad. 1: Field enhancement near one electrode is required. The most common methods used in practice for this purpose are point-to-plane and wire-in-cylinder geometries. The point-to-plane is convenient for comparisons with model calculations and the wire-in-cylinder is most suitable for gas treatment where the residence time in the cylinder is an important parameter especially for the plasmachemical processes. Surface roughness can be expected to be important for field enhancement. Recent photographs taken at TUE show that the streamer is connected to the anode on a spot with a dimension in the order of one pixel of the CCD camera used, i.e. ~20 μm. The corona current is ~1 A, so this leads to a current density of ~3 10^9 A/m^2. Erosion (or sputtering) of the anode can be expected in such a case. In laboratory experiments this is not a problem and these aspects have not been studied in detail. For large-scale, long-term application it may become an important factor in maintenance cost.

Ad. 2: The breakdown field strength in a uniform gap with atmospheric air is in the order of 3 kV/mm. This implies that a free electron gains on average several eV of energy from the field in-between collisions. The ionization energy of air molecules is roughly 10 eV. Nevertheless there will be electrons in the tail of the electron energy distribution function that have enough energy to cause ionization. Near a surface roughness much higher field strengths are readily obtained. Field emission cannot occur, however, because the electrons are drawn towards the anode.

Ad. 3: The first electron, which should start the discharge, can be provided in two ways. Cosmic radiation produces them at a rate of ~1 el/mm^{3}s. This leads to rather low background electron densities of 10^3-10^6 el/cm^3. This can imply that it takes some time for an electron to be at the right place, i.e. a region where the electric field is high enough. This time is called inception time lag and in practice it varies from about 1 ns to many microseconds. Another process that can provide electrons is field detachment from negative ions. This effect can be important when ions of a previous discharge are still present. It occurs in the self-repetitive DC corona and it causes the streamer to choose the path of its predecessor. In most applications of pulsed corona it does not occur due to the low repetition rate (~100 Hz).

Ad. 4: When the first electron has caused an ionization there are two electrons left that again start moving in the electric field and ionize again etc. In this way the so-called avalanche builds up. This process continues until the space charge of the slow ions that are left behind cancels the applied electric field. The avalanche can also stop at the anode before it is complete. In such a case the avalanche extinguishes. The length required to build up a complete avalanche is called the critical length; at 1 bar it is in the order of 1 mm [2].

Ad. 5: The space charge region cancels the field between itself and the anode, but it enhances the field in the direction towards the cathode. A free electron at the right position in this area can start a new avalanche. However, the background electron has by now disappeared from the gap due to drift. A process that can provide new electrons is photoionization. This is caused by VUV resonance photons of N_2 that are absorbed by O_2. Only the photons that originate in the tail of the lineprofile of N_2 can travel far enough, but in principle one electron is sufficient. This explanation cannot be used for discharges in e.g. pure N_2 or noble gases. Unfortunately however, data on photoionization in theses cases is unavailable. In case of N_2-O_2 mixtures only one paper is known which gives quantitative data [3]. Computer models of streamer propagation are also made without photoionization. An artificial background electron density is then required for starting new avalanches. Although such a background is not realistic, the results are very similar to models that do include photoionization.

Ad. 6: The electrons of the new avalanche cancel the previous space charge but they create a new one closer to the cathode. It is found that a so-called stability field of 5 kV/cm is sufficient to continue the propagation of the streamer channel. A cathode sheath builds up when the avalanche reaches the cathode [4]. This process is usually not considered in streamer propagation models. If the power supply can continue to deliver current the temperature of the channel will increase due to Joule heating, then its resistance will drop and the discharge may develop in to an arc.

In this paper the situation is considered that the corona current stops after the streamer head reaches the cathode. Many processes continue to occur in the gap after the discharge has stopped. The ones that are often important for further physical and chemical processes are:

1. Attachment
2. Recombination
3. Diffusion
4. Vibrational relaxation
5. Metastable quenching
6. Radical reactions

Ad. 1: Attachment is the formation of negative ions when low energy electrons combine with atoms or molecules. Not all particles form negative ions, examples are the noble gases and also nitrogen molecules. Some molecules that easily form negative ions are O_2, H_2O and CO_2. The conductivity of a plasma is strongly influenced by the capturing of low energy electrons: the light and mobile electrons are replaced by heavy ions. Therefore the field strength for sustaining a certain current is much higher in an electronegative gas. This effect partly explains e.g. why a small amount of water can have a big impact on a noble gas discharge or the difference between dry air and flue gas.

Ad. 2: Recombination of positive ions and electrons (or negative ions) leads back to the neutral gas as before the discharge pulse. It can cause some additional effects such as the

emission of recombination radiation which can be used to determine the electron energy if its intensity is sufficient. In case of a corona discharge this is not to be expected. Further it can lead to the formation of excited states that have high chemical activity. The recombination time in the atmospheric corona discharge is estimated to be in the order of 1 μs. It has not been measured up to now. The time interval required for a corona pulse in order not to notice its predecessor is found in experiments to be in the order of 1 ms. This is probably due to negative ions and/or metastables that have much longer lifetimes than electrons.

Ad. 3: The active particles in a corona discharge are formed in a thin channel (diameter ~200 μm). It is often the intention to treat the whole gas volume, so one may wonder if diffusion is able to spread the radicals significantly. From Schlieren pictures (see next section) it is seen that the streamer diameter increases to ~2 mm in 200 μs. So, this increases the treated volume but still a single discharge pulse treats only a volume fraction in the order of 10^{-3}. This explains why in practice a residence time of several seconds is usually required for a complete treatment. The turbulence created by the corona pulses probably helps to mix the gas but this effect has not been studied in detail up to now.

Ad. 4: The high-energy electrons in the streamer head cause ionization and excitation to higher electronic states. The most important example is the $N_2(C)$-state because it leads to the UV emission of the so-called Second Positive System. The excitation also leads to high vibrational relaxation by which these states decay through collisions to rotational and translational excitation. This is the same as saying that the gas is heated. Emission spectroscopy can give quantitative results about these processes (see next section).

Ad. 5: Excited metastable states cannot lose their energy by emission of a photon. Another process to take away energy from them is by collisional quenching. Metastables are often close to resonant levels, so a collision with a low energy electron can cause them to become resonant, lose the energy within ~1 μs by emitting a VUV photon and become a ground state. It is also possible that they transfer all their energy to a different molecule. In this way quenching of a N_2 metastable can cause dissociation of a water molecule. This process is considered to give an important contribution to the formation of OH radicals in humid air or flue gas. No quantitative studies are available at present, however.

Ad. 6: Radicals are formed by electron impact dissociation of molecules in the streamer head region. The dissociation energy is usually somewhat lower than the ionization energy. Primary radicals are the ones created directly by these collisions, e.g. O, H, OH and N. They may react rapidly with molecules to form secondary radicals such as HO_2 or O_3. If contaminations such as SO_2 or NO are present O, HO2 and O3 can oxidize them to acids. The N radical can reduce NO to N_2. How much this happens depends on the gas composition. This is one of the major application areas of corona discharges [1].

Diagnostics

1. Cloud chamber tracks

The first recordings of avalanches have been made by Raether [5]. He used a cloud chamber to grow droplets around the ions that are left behind. These droplets are photographed through light scattering. Such pictures are extremely sensitive but have, however, no time resolution. Fig. 1 is obtained from the original paper by Raether from 1939. He used a plan parallel gap with N_2 at 150 Torr. The length of the avalanche is of the order of 1 cm.

Fig. 1: Cloud track picture of a single avalanche, cathode at the left (by H. Raether, [5])

2. Streak pictures

The next method, used by Wagner, is streak photography using an image-intensified camera [6]. The pictures obtained with such a system show one spatial dimension versus time. Figure 2 gives an example.

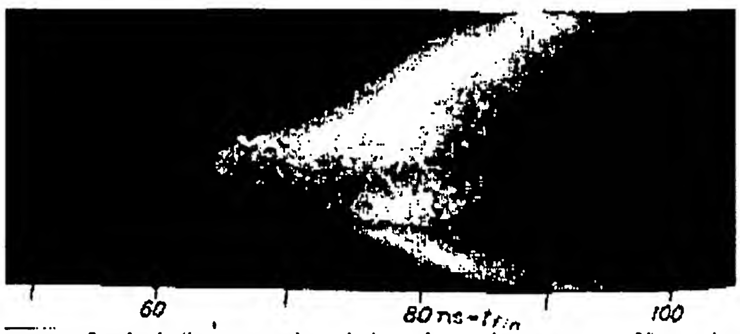

Fig 2: Streak picture of cathode (bottom) and anode (top) directed streamer in a 30 mm plane gap with 378 Torr N_2 (by K.H. Wagner, [6]).

In fig. 2 it can be seen that in the case of plane electrodes the streamer starts in the middle of the gap and it develops towards cathode and anode. Two phases of developments are distinguished: from 60 to 70 ns with a propagation velocity of ~2-3 10^5 m/s and from 70 to 80 the speed becomes ~10^6 m/s.

3. Photography

The streamer discharge is difficult to access by experiments due to its transient nature. Its total duration is in the order of 10 ns and the streamer head moves along its own thickness in 0.1 ns. This resolution is still not obtained with state-of-the-art cameras. Present day intensified CCD camera's can be gated down to about 1 ns. The sensitivity of these cameras is becoming close to that of photomultipliers, this is quite sufficient to allow single shot exposures. An example is given in fig. 3, which is a photograph of a point-plane corona discharge in a 25 mm gap in ambient air using a voltage pulse of 25 kV with a rise time of 30 ns. The camera used here is an Andor Technology ICCD-452 having the following specifications:

- 1024 x 1024 pixels
- pixel size 13 µm x 13µm

- sensitivity 180-850 nm
- minimum optical gate 0.8 ns
- full width at half maximum 21 µm
- gain up to 3600

Fig 3: Pictures of streamer propagation in a point-to-plate gap using a 0.8 ns intensifier gate, real size per frame ~3x3 cm² (picture by A H.F M Baede)

Figure 3 shows three pictures at different trigger moments. The time lap between the left and the right pictures is ~40 ns. This value cannot be determined very accurate in the present set-up used because of jitter in the power supply and the corona initiation. The dark spots of the streamer heads are overexposed in these pictures; therefore they look larger than they are. An analysis of their full width at half maximum shows a value of 150 µm for all streamers observed under this condition [7]. Figure 4 shows similar pictures in a wire-cylinder gap with a cylinder having an inner diameter of 290 mm. A voltage pulse of 100 kV is used here having a rise time of 20 ns.

Fig 4: Four stages in the expansion of a corona discharge in a 29 cm cylinder Opening time 5 ns at 10, 20, 30 and 40 ns after the initial rise of the voltage pulse of 200 kV with 20 ns rise time, real size last frame ~30x30 cm² (by P P M Blom, [8])

Figures 3 and 4 show similarities in the way the streamer heads move from anode to cathode but in the streamer diameters are quite different, in fig. 3 they are ~0.2 mm and in fig. 4 ~1 cm. Comparing these figures to 2-D modeling of streamer propagation one finds that the results of fig. 3 are close to those obtained by simulations. The situation of fig. 4 is different due to the extreme rate of rise of the voltage. It resembles the fast ionization wave (FIW) where electron energies are higher than in the corona discharge [9]. This FIW is the transition region to runaway electrons that can have keV's of energy as has been measured by detection of X-rays [10].

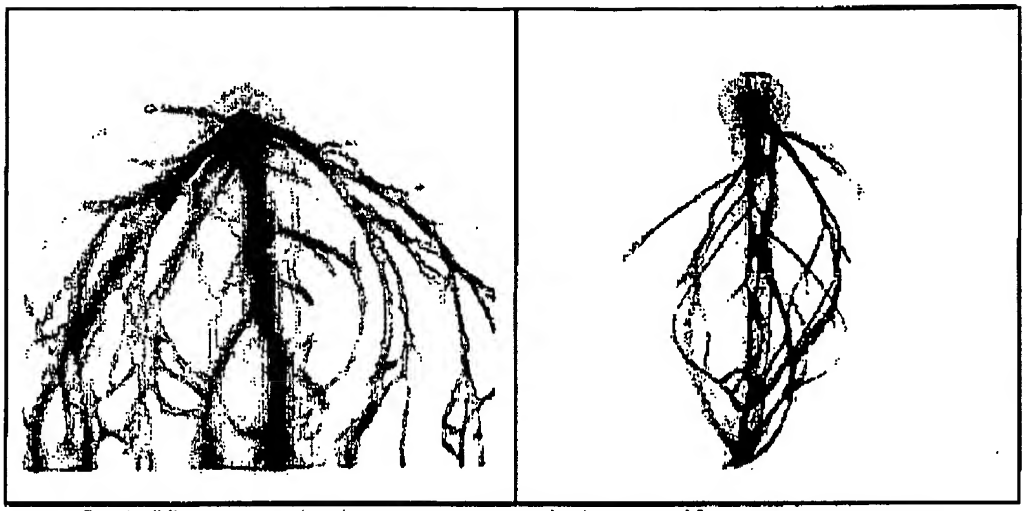

Fig. 5. CCD photographs of a point-wire corona discharge in a 25 mm point-wire gap in air
Left. view perpendicular to wire, right. view parallel with wire

Figure 5 shows two examples of pictures taken with exposure times of 100 ns, i.e. a time integrated picture of the discharge crossing the gap. In the left part one sees that the streamers spread out to a width that is larger than the point-wire distance. The right figure shows how the streamers bend out in the middle of the gap but they redirect towards the wire.

4. Schlieren photography

The path created by the corona streamer has a composition that is different from the surrounding gas. It can also have an enhanced temperature. Therefore its refractive index differs from its background. Such a difference can be visualized by Schlieren photography. This can be performed in three ways: 1. standard Schlieren methods are sensitive to the gradient in the refractive index, dn/dx, 2. interferometry, which is related directly to the refractive index n and 3. shadowgraphy which is proportional to d^2n/dx^2 [2, 11]. Figure 6 is obtained by a standard knife-edge method.

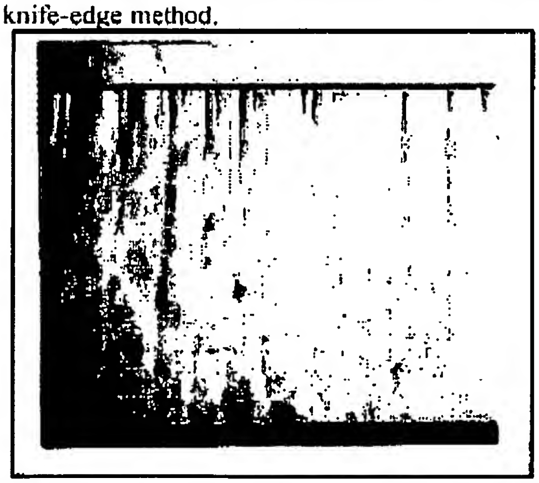

Fig. 6. Schlieren photograph of wire-plane pulsed corona taken 100 μs after the voltage pulse
(by Y L M. Creyghton, [2])

The remarkable result of Schlieren pictures of a corona discharge is that its appearance is most clearly 50 to 100 μs after the voltage pulse. Within 1 μs the streamer paths are not observed. The explanation for this is that the fast electrons first cause ionization and vibrational excitation that does not affect n. After vibrational de-excitation to rotations and translations the streamer channel gets heated and shows up more clearly. A time constant of 100 μs for this process is reasonable.

5. Emission spectroscopy

The optical emission of the corona streamer can be analyzed by spectroscopic techniques. Monochromators have sufficient resolution for a discharge at 1 bar but main problems are the low intensity and the short duration. A technique that is well suited in this case is the time-correlated single-photon counting method. It uses an optical trigger to determine the timing of the photon to be counted. A time-to-amplitude converter can be included to obtain a time resolution down to 0.1 ns. Several slightly different version of this method are in use, not only for the pulsed corona [2, 12] but also for the self-repetitive discharge [13-15].

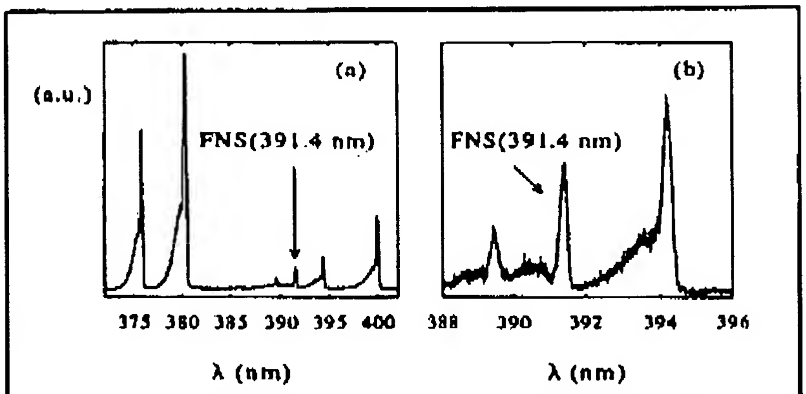

Fig. 7. Emission spectrum of a pulsed corona discharge showing parts of N_2 SPS and FNS (by Y.L.M. Creyghton, [2]).

Figure 7 gives an example of a part of the nitrogen spectrum in the near UV. It shows part of the Second Positive System of N_2 and the First Negative System of N_2^+. Because these systems have very different excitation levels the ratio of their intensities is a measure of the electron energy. Using this effect one obtains ~10 eV for electrons in the streamer head [2].

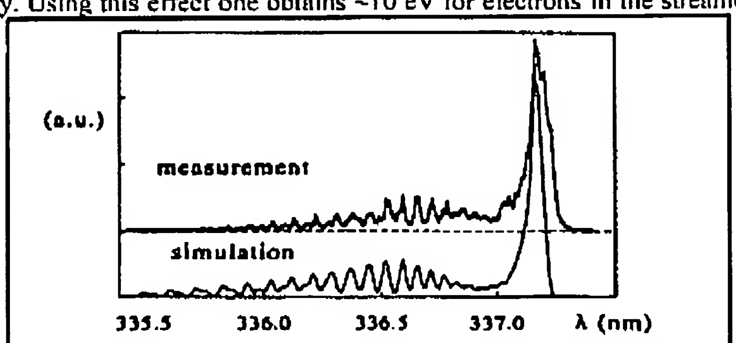

Fig. 8: Measured and calculated rotational structure of the N2 SPS (0-0) transition in the secondary streamer phase of a pulsed corona (by Y L M Creyghton, [2])

In figure 8 the rotational structure of the SPS (0-0) transition is resolved. It is compared with a calculated spectrum with a rotational temperature of 350 K. The spectrum shown here is recorded in a time interval of 50-200 ns after rise of the voltage pulse, so the secondary streamer is observed [2]. It shows that the gas is still hardly heated at this instant.
The width of the measured spectral line can also be used. A nice example of it is given in [16] where the Stark broadening of the H-β line is used to determine the electron density. The result of 10^{15} cm^{-3} is, however, one order of magnitude higher than values obtained from simulations [1].

6. Absorption spectroscopy
Atoms and molecules can absorb light of specific wavelengths. The advantage of absorption is that it easily gives quantitative information on the lower level of the transition involved. Calibration is usually straightforward from known cross sections or gas mixtures. This method can be used to detect all kinds of species in a discharge (or any other gaseous system). Ozone is a well-known example but also NO, NO_2, SO_2 and NH_3 are easily determined [1, 17]. Short living excited states and radicals, created by the discharge can also be measured. A nice example is the OH ground state density in a tandem barrier discharge [18]. Absorption spectra can also be used to determine rotational temperatures [19].

7. Laser induced fluorescence
Although absorption spectroscopy is relatively easy it cannot be used in many cases because the absorption of low-density species is weak. The molecule that has absorbed radiation can emit this in other directions and also at other wavelengths, the so-called fluorescence. In that case using a strong source, e.g. a laser, can increase the signal. The sensitivity of this method is many orders of magnitude higher than the classical absorption technique. The first example of its use in a barrier discharge is the detection of OH radicals [20, 21]. Other examples are N_2^+ [22], $N_2(A)$ [23], NO [24], N [25].

Final remarks
The corona discharge at atmospheric pressure is in use and under investigation already for a long time. Its use with a pulsed power supply is of more recent date. From all information given above one may get the idea that the situation is well known. This is, however, not the case. Many processes are only estimated or assumed, e.g. field emission, photoionization, diffusion, recombination, and collisional de-excitation. The fact arising from this situation is that for e.g. values found for the electron density range from 3 10^{13} to 2 10^{15} cm^{-3}. For OH radicals very few measurements are available. In [18] a volume-averaged value of 10^{15} cm^{-3} is obtained. This implies a density inside the streamer that is much higher than values obtained from simulations [1].
So the problem that is faced is to make the results more quantitative. This must be done from theory and experiment since not all details can be measured using present day equipment. All methods mentioned above can be used for this purpose with detection possibilities that have only recently become available, e.g. generation-IV CCD-camera's. New techniques can probably be added. On can think of Coherent Anti-Stokes Raman Scattering to be used in rough environments. It is already being tested in barrier discharges [26]. Another possibility is Cavity Ringdown Spectroscopy, which is an extremely sensitive absorption technique that could be used to determine short living intermediate species.
The final aim should be to develop sufficient understanding of the discharge in order to predict and develop applications.

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